Prospects to measure the Higgs boson properties in ATLAS

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As soon as a significant signal in one of the Higgs boson discovery channels is observed, it will be important to establish its nature. To do this, a precise measurements of its properties is important. In this article the prospects to measure the Higgs boson mass, width, spin and CP-quantum numbers, couplings to the known Standard Model particles and self-couplings by the ATLAS experiment are summarized.

1 Introduction

The Standard Model (SM) is in excellent agreement with all experimental measurements. However, one of the important issues of the theory, the mechanism of electroweak symmetry breaking, is not yet verified. The Higgs mechanism is a possible solution but requires at least the experimental discovery of the Higgs boson. The LHC experiments, ATLAS and CMS, will be able to discover the SM Higgs boson in the allowed mass range from the lower limit set at LEP up to ~ 1000 GeV/c^2 for an integrated luminosity of 30 fb^{-1}. After discovery, the properties of the discovered particle have to be investigated in detail.

1.1 Measurement of the Higgs boson mass and width

A precise measurement of the Higgs boson mass can be extracted from those channels where the Higgs decay products can be reconstructed, as in the case of $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell$. Assuming an integrated luminosity of 300 fb^{-1} the Higgs boson mass can be measured directly with a precision of $\sim 0.1\%$ over the mass range 100 - 400 GeV/c^2, as shown in Fig. 1 (left). The error is dominated by the absolute knowledge of the lepton or photon energy scale which is assumed to be 0.1%. For larger masses the precision degrades due to the larger Higgs boson width and the increase of the statistical error. However, even for masses around 700 GeV/c^2 a precision of about 1% can be reached [1].

A direct measurement of the Higgs Boson width is impossible below 200 GeV/c^2. For a Higgs boson mass above 250 GeV/c^2 the detector resolution is sufficient for probing the intrinsic width with a precision of about 6% [1].

1.2 Measurement of the Higgs boson spin and CP eigenvalues

One of the first priorities must be a determination of the spin and the CP quantum numbers. An analysis to probe these quantum numbers was presented in Ref.[2,3]. The decay mode $H \to ZZ \to 4\ell$ is used in the mass range above 200 GeV/c^2 to extract information on spin and CP by studying two distributions of the decay correlations: the polar angle of the decay leptons relative to the Z boson and the angle between the decay planes of the two Z in the rest frame of the Higgs boson.
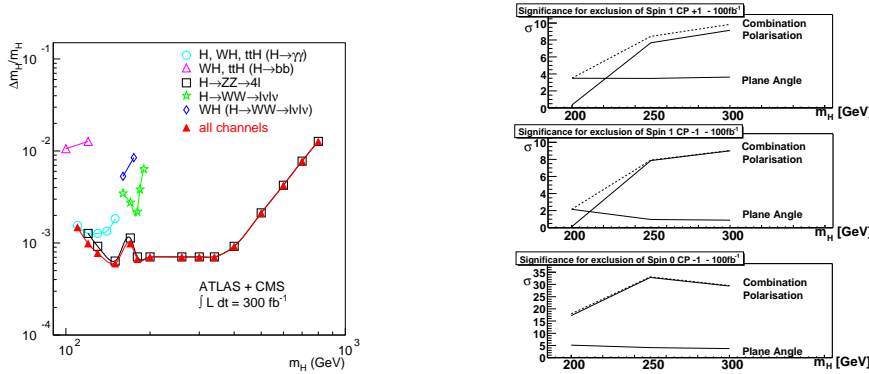

Figure 1: Left: The expected precision of the Higgs boson mass measurement. Right: Discrimination significance in 1^+, 1^- and 0^- scenario using $H \to ZZ \to 4\ell$.

In the high mass region ($m_H \geq 250\,\mathrm{GeV/c^2}$) the angular correlations yield good discrimination power between the SM (0^+) Higgs boson, and 1^+, 1^-, 0^- scenarios (see Fig. 1 right). In this context it should be noted that the Spin 1 hypothesis is also ruled out by observing non-zero $H\gamma\gamma$ and Hgg couplings. All scenarios considered can be separated from the SM with a significance of more than 8 σ with an integrated luminosity of 100 fb^{-1}. The decay plane angle correlation becomes more important for lower Higgs boson masses, where the discrimination power of the polar angle variable decreases. For a Higgs boson mass below 200 GeV/c^2 information on spin and CP can be extracted from the azimuthal separation of the leptons in the vector boson fusion process $qq \to qqH \to qqWW \to qq\ell\nu\ell\nu$ [4].

1.3 Measurement of the Higgs boson coupling parameters

Based on all ATLAS simulation studies for a SM Higgs boson, a global Maximum Likelihood fit has beem performed to determine the expected accuracy on the measurement of the coupling parameters. So far, the interesting low mass region 110 GeV/c^2 to 190 GeV/c^2 has been considered in Ref.[5].

The fit takes experimental and theoretical systematic errors into account. Depending on theoretical assumptions different kinds of coupling parameters can be extracted. All fits are based on a CP-even, spin-0 Higgs boson. Hypothesis assuming that only one light Higgs boson exists, it is possible to measure ratios of Higgs boson partial widths. The assumption that there are no new particles involved in $gg \to H$ production and no extremely enhanced couplings to light fermions allows to measure ratios of Higgs Boson couplings of Z boson, τ, b and t fermion to the W boson coupling. For an integrated luminosity of 300 fb^{-1}, the ratios can be measured to 10% - 30%. With the assumption of an upper limit on the W and Z coupling and of a

Production	Decay	Mass range
Gluon Fusion	$H \to ZZ^{(*)} \to 4\ell$	110 GeV - 200 GeV
$(gg \to H)$	$H \to WW^{(*)} \to \ell\nu\,\ell\nu$	110 GeV - 200 GeV
	$H \to \gamma\gamma$	110 GeV - 150 GeV
Weak Boson	$H \to ZZ^{(*)} \to 4\ell$	110 GeV - 200 GeV
Fusion	$H \to WW^{(*)} \to \ell\nu\,\ell\nu$	110 GeV - 190 GeV
	$H \to \tau\tau \to \ell\nu\nu\,\ell\nu\nu\ (\ell\nu\nu\,\mathrm{had}\nu)$	110 GeV - 150 GeV
	$H \to \gamma\gamma$	110 GeV - 150 GeV
$t\bar{t}H$	$H \to WW^{(*)} \to \ell\nu\,\ell\nu\,(\ell\nu)$	120 GeV - 200 GeV
	$H \to b\bar{b}$	110 GeV - 140 GeV
	$H \to \gamma\gamma$	110 GeV - 120 GeV
WH	$H \to WW^{(*)} \to \ell\nu\,\ell\nu\,(\ell\nu)$	150 GeV - 190 GeV
	$H \to \gamma\gamma$	110 GeV - 120 GeV
ZH	$H \to \gamma\gamma$	110 GeV - 120 GeV

Table 1: List of all ATLAS studies used for the Maximum Likelihood fit. The mass range is the range of Higgs boson mass considered in the studies (not the discovery region).

lower limit on Γ_H, an absolute measurement of coupling parameters is possible[6]. The expected relative accuracy (Fig. 2) for this measurement is between 10% and 40%.
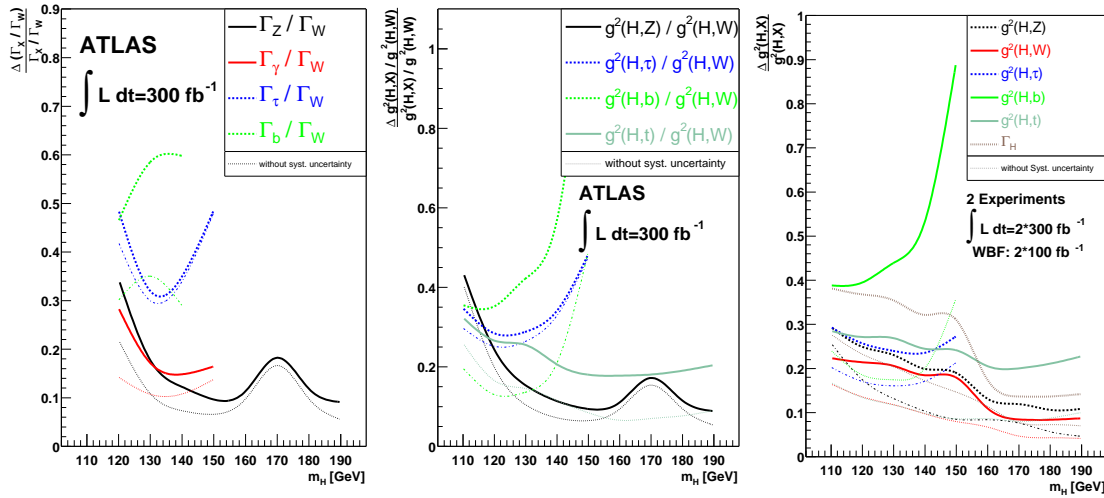

Figure 2: Expected relative error on the measurement of ratios of partial widths, coupling ratios and absolute couplings. The dotted lines give the expectation without systematic uncertainties.

1.4   Probing the Higgs boson self-coulings at LHC (SLHC)

The most important task after a Higgs boson discovery and coupling measurements is the extraction of the Higgs potential. This requires the measurement of the trilinear and quartic Higgs Boson self-coupling. Only multiple Higgs boson production can probe these directly. Since the quartic coupling is about two orders of magnitude smaller than the trilinear coupling, present studies have focussed on the determination of λ_{HHH}. Studies have shown that the $HH \to WWWW \to (\ell^{\pm}\nu jj)(\ell^{\pm}\nu jj)$ final state has the highest sensitivity for extracting information on the self-coupling parameter. A recent study[7], based parton level calculations, concludes that the LHC may rule out the case of a non-vanishing λ_{HHH} within a mass range of 150 GeV/$c^2 \le m_H \le$ 200 GeV/c^2 with a confidence level of 95%. For the upgraded LHC, assuming an integrated luminosity of 3000 fb^{-1} per experiment, it is claimed that a measurement of λ_{HHH} with 20% precision will be possible (Fig. 3). In order to derive more realistic sensitivity bounds for the Higgs boson self-coupling, more detailed simulations, which take the

detector performance into account, are needed. First preliminary studies were performed to confirm the sensitivity at the SLHC scenario[8]. However, some background contributions might have been underestimated. Further studies on this subject are currently in progress[9].
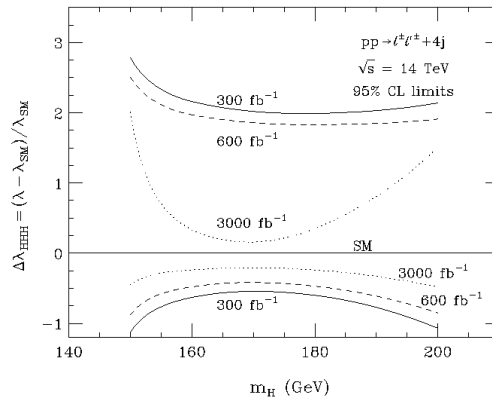

Figure 3: Sensitivity bounds for the Higgs boson self-coupling are shown for several integrated luminosity scenarios (taken from Ref.[7]).

2 Conclusion

The expected performance of both LHC experiments offers a good possibility not only to discover a Higgs boson but also to measure its properties like mass, spin/CP and couplings. For typical mass regions the precision of the mass measurement is about 0.1%. For a Higgs boson mass above 200 GeV/c^2 spin/CP sensitive measurements are possible using angular correlations in the $gg \to H \to ZZ$ channel. For the critical region of Higgs boson masses below 200 GeV/c^2 ratios of couplings squared and absolute couplings squared can be extracted with 10% to 50% relative error using moderate theoretical assumptions. A first probe of the Higgs self-coupling to determine the shape of the Higgs potential might be possible at a luminosity upgraded LHC.

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